Atmospheric Neutrino Flux: A Review of Calculations

T.K. Gaisser[a]*

[a]Bartol Research Institute, University of Delaware,
Newark, DE 19716, USA

Interpretation and understanding of the evidence for neutrino oscillations depends on knowledge of the atmospheric neutrino beam. In this talk I assess how well various features are known. The goal is to determine to what extent uncertainties in the neutrino beam may limit the conclusions about neutrino properties and which features of the evidence for neutrino oscillations are most robust.

1. Introduction

The concept of using the atmospheric neutrino beam to look for neutrino oscillations is illustrated in Fig. 1 [1]. With a single detector it is possible simultaneously to cover a range of pathlengths from ~ 10 to $\sim 10^4$ km, corresponding respectively to downward moving and upward moving neutrinos. The atmospheric neutrino beam has an energy spectrum determined by the steeply falling primary cosmic-ray spectrum, which generates the neutrinos by interactions of the cosmic ray nucleons in the atmosphere. Examples of calculated neutrino fluxes are shown in Fig. 2.

The neutrino spectrum, which falls with energy, must be folded with the rising neutrino cross section to obtain the expected event rate as a function of neutrino energy. Most neutrino interactions are in the range from a few hundred MeV to a few tens of GeV. Thus atmospheric neutrinos have the potential to probe the range $1 < L/E < 3 \times 10^4$ km/GeV. From the standard two-flavor oscillation equation,

$$P_{\nu_\mu \nu_\mu} = 1 - \sin^2 2\theta \sin^2 \left[1.27 \delta m^2 (eV^2) \frac{L_{km}}{E_{GeV}} \right], \quad (1)$$

we find, therefore, that the atmospheric neutrino beam can in principle probe down to δm^2 as small as $\sim 2 \times 10^{-5}$ eV^2. (The actual lower limit to sensitivity in δm^2 is somewhat higher than this because of the relatively large scattering angle between neutrino and lepton in charged current interactions of low energy neutrinos.)

Atmospheric neutrinos originate with the $\pi \to \mu \to e$ decay chain. Therefore at sufficiently low energy such that muons as well as pions decay, one expects

$$\frac{\nu_e + \bar{\nu}_e}{\nu_\mu + \bar{\nu}_\mu} \approx \frac{1}{2}. \quad (2)$$

The anomalous value of this ratio[2–5] (for which many sources of uncertainty cancel in the calculations) suggests neutrino oscillations involving ν_μ and/or ν_e as a possible explanation. The telltale evidence [6] for oscillations as the source of this anomaly comes from the pathlength dependence of the neutrino fluxes. The energy-dependence of the up-down asymmetry for muon-like events, coupled with the fact that events initiated by electron neutrinos appear to have the expected energy and angular dependence, indicates that the primary effect is oscillations involving muon neutrinos with large mixing and $\delta m^2 \approx 3 \times 10^{-3}$ eV^2 [6].

In the remainder of this paper I will describe how the geomagnetic field affects the interpretation of the atmospheric neutrino data, review the primary cosmic-ray spectrum, discuss the uncertainties in the treatment of pion production and mention the comparison of the calculations to measurements of muons high in the atmosphere. It is important to review these points at this time because of the recent publication of two new calculations [7,8], which are three-dimensional, as compared to previous one-dimensional calcula-

*Research supported in part by the U.S. Department of Energy under Grant No. DE-FG02-91ER40626

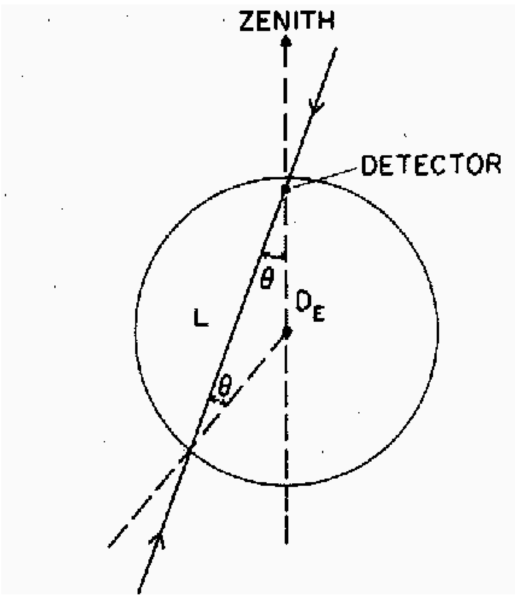

Figure 1. Illustration of up-down symmetry of atmospheric neutrinos in the absence of effects of the geomagnetic field and assuming no oscillations.

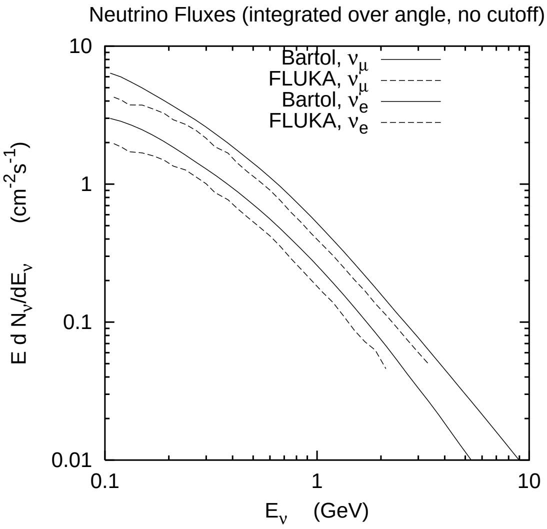

Figure 2. Fluxes of atmospheric neutrinos from two calculations: FLUKA [7], dashed; Bartol [24], solid.

tions.

2. Geomagnetic field effects

In the absence of oscillations, the only significant deviation from isotropy of the atmospheric neutrino beam is caused by the geomagnetic field, which prevents low energy primary cosmic rays from reaching the atmosphere at low geomagnetic latitudes. For example, at Kamioka the geomagnetic cutoff is $\approx$ 10 GeV for primary protons near the vertical. The downward neutrino flux at Kamioka is therefore lower than, for example, at Soudan, where the vertical cutoff is negligible. Approximately half the downward neutrinos with $E_\nu < 1$ GeV at Soudan come from primary protons with $E < 10$ GeV. This contribution is absent from the downward neutrino flux at Kamiokande. As a consequence the downward flux of sub-GeV neutrinos at Kamiokande is roughly half that at Soudan. The neutrino flux from the lower hemisphere is similar at the two detectors and intermediate between the downward fluxes at the two locations. This is because the neutrinos from below are produced over a large fraction of the Earth's surface and so average over a range of high and low geomagnetic cutoffs. Thus the up-down asymmetry at each detector location is a combination of geomagnetic effects together with the effects of any oscillations that may be present, and the combination depends on detector location. Moreover, the geomagnetic effects become less important as energy increases. It is therefore useful to start by considering the atmospheric neutrino analysis without the geomagnetic field.

For a flux of primary cosmic rays that is spatially isotropic, the atmosphere is a spherical shell source of neutrinos with equal luminosity per unit volume independent of latitude and longitude. The number of neutrinos produced per unit volume of atmosphere into solid angle $d\Omega$,

$$S(\theta, h) \;=\; \frac{dN_\nu}{d\Omega\, dV}, \tag{3}$$

depends only on local zenith angle, θ, and altitude, h. In these circumstances one can show from the geometrical construction of Fig. 1, that the neutrino flux is up-down symmetric; i.e. symmetric about $\cos\theta \leftrightarrow -\cos\theta$. Since neutrinos from decay of pions, muons and other secondary cosmic rays are produced over a range of altitudes peaking around 15 to 20 km above sea level [9], it follows that local variations in surface altitude introduce a negligible deviation from this symmetry. The symmetry also requires that differences caused by local variations of pressure are negligible.

A detector like Super-Kamiokande has an acceptance that is up-down symmetric. In the absence of geomagnetic effects, therefore, a simple measurement of the up-down asymmetry as a function of energy is a probe of neutrinos oscillations. Therefore the simplest and most robust evidence for oscillations is a deviation from up-down symmetry in an energy range high enough so geomagnetic effects are small. Fig. 3 [10] shows the distribution of neutrino energy for four classes of neutrino interactions. The corresponding distributions in energy per nucleon for the primary cosmic-rays are about a factor of ten higher. Thus the median primary of the multi-GeV events is about 50 GeV/nucleon, which is high enough so that geomagnetic effects are unimportant. Neutrino-induced upward muons provide a higher energy sample, but it is not possible to make a simple up-down comparison because the downward muon flux is dominated by muons produced from pion decay in the atmosphere rather than by interactions of neutrinos.

Interpreting the up-down asymmetry of the neutrino fluxes in the GeV range and below requires that the geomagnetic effects be well understood. Geomagnetic effects on the primary cos-

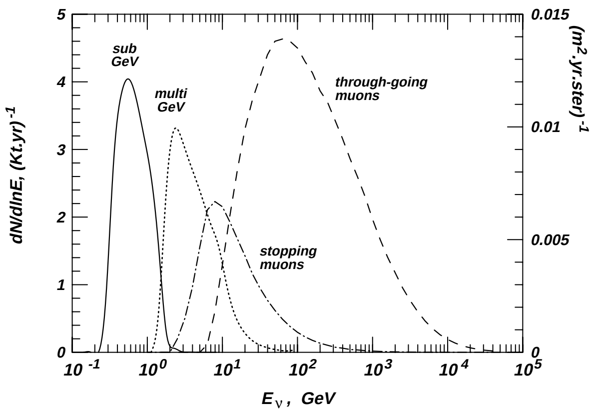

Figure 3. Distribution of neutrino energies for various classes of atmospheric neutrino events.

mic radiation are indeed very well understood. They form the basis for an entire subfield of cosmic-ray physics [11]. Low energy particles (few GeV) at low geomagnetic latitudes cannot reach the atmosphere to interact. Particles of intermediate energy ($\sim$ 10 to 20 GeV) that reach the atmosphere show a strong east-west asymmetry, while high energy particles ($\sim$ 100 GeV and higher) are essentially unaffected by the geomagnetic field.

The east-west effect is a consequence of bending of positive primaries in the geomagnetic field. In fact, it was the observation of the excess of primary cosmic rays from the west [12,13] from which it could be deduced that the primaries were predominantly positively charged. The expected azimuthal dependence of the neutrino flux associated with the east-west effect is the same whether or not the neutrinos oscillate because the distribution of pathlengths that contribute to a particular zenith angle band is independent of azimuth. Comparison between expected and observed azimuthal distributions is therefore a good check of the systematics of the whole chain of data analysis and calculations [14]. The measurements show the expected azimuthal dependence for both muon and electron neutrinos [15], indicating that the geomagnetic effects are well understood.

3. Primary spectrum

A standard procedure for calculating the flux of atmospheric neutrinos is to generate atmospheric cascades for a spectrum of primary protons and nuclei and form the neutrino spectra in the absence of the geomagnetic fields. The resulting neutrino spectra can be filtered through the geomagnetic configuration relevant for a particular detector location, discarding those neutrinos produced by primaries that would not have reached the atmosphere. An alternative approach [16] starts from the measured muon fluxes high in the atmosphere and uses the genetic relation between neutrinos and muons to obtain the muon spectrum. In either case, the normalization of the neutrino flux depends on the absolute normalization of a measured spectrum of charged particles (either the primary cosmic rays or the muons). The advantage of starting with the muons is that one bypasses uncertainties in knowledge of pion production, which have a similar effect on both neutrinos and muons. A disadvantage is that the acceptance for muons is sensitive to details of propagation in the geomagnetic field. In addition, the measurements of the primary flux are made with relatively long exposures at or above the atmosphere while the relevant muon measurements are generally made during a short balloon ascent.

The mixture of nuclei in the primary spectrum is such that approximately 80% of nucleons in the cosmic radiation are free protons, 15% are bound in alpha particles and the remainder are in heavier nuclei. Spectra of protons and helium with $E < 100$ GeV/nucleon have been measured at the top of the atmosphere in a series of balloon-borne spectrometer experiments. Recent measurements [17–21] cluster around a lower normalization [22] than an earlier standard reference [23]. At higher energy, measurements have so far been possible only with calorimeters, which, because of punchthrough, may have larger systematic uncertainties. The data are summarized in Fig. 4.

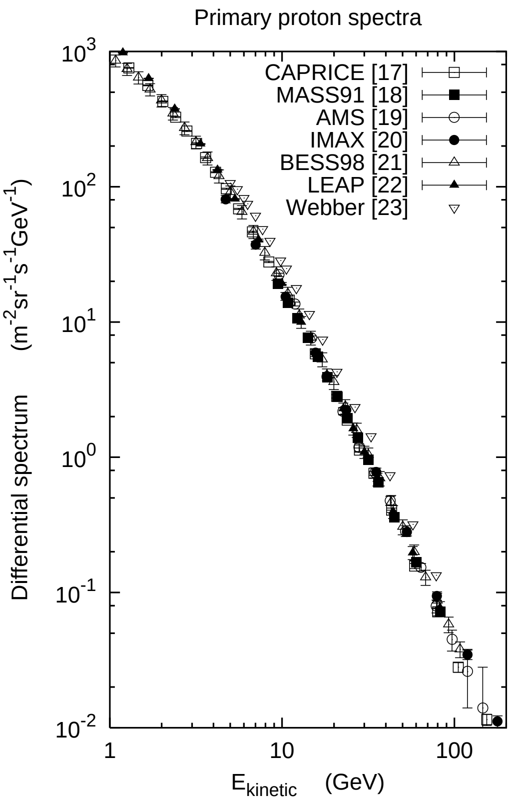

Figure 4. Primary spectra.

4. Comparison of calculations

There are now five independent calculations of the neutrino spectrum that start from the primary cosmic-ray spectrum filtered by the geomagnetic field. The calculations of Refs. [24–26] are one-dimensional, assigning all produced neutrinos the directions of the primary particle that produced them. The ingredients of these calculations have been compared previously [27]. Recently two three-dimensional calculations have been published [7,8]. Treatment of the geomagnetic cutoffs, which now depend on 4 variables instead of 2, makes the calculation significantly more complex. These calculations are very important because they check the major, technical simplifying assumption made by the previous calculations.

A conclusion reported in Ref. [7] is that differences for predicted event rates and how they depend on direction and energy are relatively small between one-dimensional and three dimensional versions of the same calculation. This has the important consequence that the simpler one-dimensional calculations can be used to explore the consequences of uncertainties in input to the calculations. Fig. 2 compares the Bartol neutrino flux [24] with the 3-dimensional flux of Ref. [7]. Both calculations use the primary spectrum of Ref. [24], and the geomagnetic field has been turned off. Most of the difference, therefore, is presumed to be caused by differences in the treatment of pion production.

5. Pion production

Most pions with $E < 100$ GeV in the atmosphere decay before they interact. Therefore, for neutrinos in the sub- and multi-GeV range, only interactions of protons and helium play a significant role. The most important information needed about these interactions is the inclusive cross sections for pion production. The important range of interaction energies extends up to ~ 100 GeV for sub-GeV and ~ 1 TeV for multi-GeV interactions. The most probable energy of a primary proton for a sub-GeV event at Super-K is ≈ 20 GeV. The corresponding number at Soudan is about 10 GeV because of the lower geomagnetic cutoff. The parent energies for multi-GeV events are correspondingly higher. The distributions of secondary nucleons is also important because a significant fraction of the neutrino production occurs in secondary or tertiary interactions of the nucleons. Neutral pions (and η mesons) are also important in the sense that energy deposited in the electromagnetic part of the cascade is not available for production of neutrinos. Distributions of kaons begin to be important for multi-GeV events (and they are dominant for neutrino-induced upward muons [24]).

Data on pion production have been discussed recently in Ref. [10]. Existing measurements cover a significant fraction, but not all, of the relevant range of phase space for charged pion production in proton collisions on beryllium and aluminum. New, more precise measurements covering all phase for proton interactions on a range of light nuclei (including nitrogen and oxygen) would be of great interest. Use of a helium beam would also be of interest.

The difference between the neutrino calculations shown in Fig. 2 most probably mainly reflects a difference in the fraction of energy going into production of charged pions. The calculation of Ref. [24] uses a phenomenological hadronic event generator (TARGET) developed for cosmic-ray cascade calculations. FLUKA [30] uses a more sophisticated microscopic model of particle production with intranuclear cascading. It incorporates the event generator as an integral part of a cascade code capable of simulating interactions and cascades in complex detector geometries. The philosophies are quite different. The FLUKA interaction model is tested and adjusted by comparing directly to double differential cross sections for a wide range of data sets *as measured*

$$(e.g.\ \ E_\pi \frac{dN_\pi(E_p)}{dp_L\, d^2p_T}\ ).$$

The strategy with TARGET is to fit p_T distributions at each longitudinal momentum, p_L, extrapolate into unmeasured regions of phase space at each p_L, and integrate to obtain the energy flow into each secondary channel,

$$E_\pi \frac{dN_\pi(E_p)}{dE_\pi}.$$

A detailed investigation of the sources of difference between these two models and others [25], and their implications, is currently in progress.

6. Comparison to atmospheric muons

Most muons and neutrinos are produced between 10 and 30 kilometer altitudes [9] in closely related processes. Measurements of muons at these altitudes therefore in principle provide a check of the neutrino calculations in which the uncertainties in pion production cancel to the extent that they are common to both the neutrinos and the muons. Recently there have been several comprehensive measurements of muons during ascent of balloon payloads [18,28,29], and some discrepancies with calculations have been noted. Generally, the agreement is best at float altitude, where only the first interaction plays a role. An important limitation to the use of muons to normalize the neutrinos, however, is that the muons are more sensitive to details of the calculation. For example, since most muons decay in flight, a change in interaction lengths, which moves the cascade up or down, can change the muon flux at a particular altitude without changing the corresponding neutrino flux, which is an integral over the whole atmosphere. Since muons follow curved trajectories in the geomagnetic field, approximating by straight lines can have a similar effect (by moving the muon decays lower in the atmosphere). In addition, since positive and negative muons have opposite curvature [31] their response to cutoffs of the primary cosmic radiation are somewhat different. Three-dimensional calculations of atmospheric muons are in progress. [32].

7. Summary

- The observed pathlength dependence of the muon-like events in Super-Kamiokande [6] points to neutrino oscillations as the source of the atmospheric neutrino anomaly.

- Three-dimensional calculations of the atmospheric neutrino flux remove an important approximation present in previous calculations. It appears, however, that the simpler one-dimensional calculations are adequate for exploring differences among calculations.

- Uncertainty in the normalization of the primary spectrum is now reduced to $\approx \pm 15\%$, so the main remaining source of uncertainty is the representation of pion production.

- If the neutrino flux is significantly lower than calculated in Refs. [24] and [25], then there is a potential problem accounting for the relatively large number of electron-like events seen in SuperKamiokande within a predominantly $\nu_\mu \leftrightarrow \nu_\tau$ oscillation scheme.

- New measurements of atmospheric muons are being considered in airplanes and with slow balloon ascents.

- Uncertainties in expected event rates due to the imprecise knowledge of neutrino cross sections in the GeV energy range have not been discussed here, but may be important. [33]

Acknowledgments. I am grateful to Todor Stanev and Ralph Engel for collaboration on this work and to Todor Stanev for reading the manuscript. I thank Giuseppe Battistoni and Alfredo Ferrari for providing information about the calculation of Ref. [7]. I also thank John Ellis and Alvaro De Rujula for hospitality during "Neutrino Summer" at CERN where I began work on this talk.

REFERENCES

1. D. Ayres *et al.*, Phys. Rev. D29 (1984) 902.
2. R. Becker-Szendy *et al.* (IMB Collaboration), Phys. Rev. D46 (1992) 3720 and references therein.
3. Y. Fukuda *al.* (Kamiokande Collaboration) Phys. Lett. B335 (1994) 237 and references therein.
4. W.W.M. Allison *et al.* (Soudan Collaboration), Phys. Lett. B391 (1997) 491.
5. Y. Fukuda *et al.*, Phys. Lett. B433 (1998) 9 (sub-GeV) and B436 (1998) 33 (multi-GeV).
6. Y. Fukuda *et al.*, (Super-Kamiokande Collaboration) Phys. Rev. Letters 81 (1998) 1562. See also Kate Scholberg in Proc. 8th Int. Workshop on Neutrino Telescopes (ed. Milla Baldo Ceolin, 1999) p. 183 and M. Nakahata, TAUP99 (these Proceedings).
7. G. Battistoni *et al.*,, hep-ph/9907408, Astropart. Phys. (to be published).
8. Y. Tserkovnyak *et al.*, hep-ph/9907450.
9. T.K. Gaisser & Todor Stanev, Phys. Rev. D57 (1998) 1977.

10. Ralph Engel, T.K. Gaisser & Todor Stanev, hep-ph/9911394, Physics Letters B (to be published).
11. A.M. Hillas *Cosmic Rays*, (Pergamon Press, 1972) Chapter 2.
12. Thomas H. Johnson, Phys. Rev. 43 (1933) 834. See also Thomas H. Johnson & E.C. Street, Phys. Rev. 44 (1933) 125.
13. L.W. Alvarez & A.H. Compton, Phys. Rev. 43 (1933) 835.
14. Paolo Lipari, Todor Stanev & T.K. Gaisser, Phys. Rev. D58 (1998) 073003.
15. T. Futagami *et al.*, Phys. Rev. Letters 82 (1999) 5194.
16. D.H. Perkins, Astroparticle Physics 2 (1994) 249.
17. M. Boezio *et al.*, Ap.J. 518 (1999) 457.
18. R. Bellotti *et al.* Phys. Rev. D60 (1999) 052002.
19. AMS Collaboration, Phys. Letters (to be published).
20. W. Menn *et al.*, Proc. 25th Int. Cosmic Ray Conf. (Durban) vol. 3 (1997) 409.
21. T. Sanuki *et al.* Proc. 26th Int. Cosmic Ray Conf. (Salt Lake City) vol. 3 (1999) 93.
22. E.S. Seo *et al.* (LEAP) Ap.J. 378 (1991) 763.
23. W.R. Webber, R.L. Golden & S.A. Stephens, Proc. 20th Int. Cosmic Ray Conf. (Moscow) vol. 1 (1987) 325.
24. Vivek Agrawal, T.K. Gaisser, Paolo Lipari & Todor Stanev, Phys. Rev. D53 (1996) 1314.
25. M. Honda, T. Kajita, K. Kasahara & S. Midorikawa, Phys. Rev. D52 (1995) 4985.
26. E.V. Bugaev & V.A. Naumov, Phys. Lett. B232 (1989) 391.
27. T.K. Gaisser, M. Honda, K. Kasahara, H. Lee, S. Midorikawa, V. Naumov & Todor Stanev, Phys. Rev. D54 (1996) 5578.
28. M. Boezio *et al.*, Phys. Rev. Letters 82 (1999) 4757.
29. S. Coutu *et al.*, Proc. 26th Int. Cosmic Ray Conf. (Salt Lake City) vol. 2 (1999) 68.
30. A. Fassò, A. Ferrari, J. Ranft and P.R. Sala, Proc. of the 3rd Workshop on Simulating Accelerator Radiation Environment, SARE-3, KEK-Tsukuba, May 7-9, 1997, (H. Hirayama, ed.) KEK Report 97-5, p. 32 (1997).
31. Thomas H. Johnson, Phys. Rev. 59 (1941) 11.
32. T. Stanev, S. Coutu, T.K. Gaisser & G. Barr, Proc. 26th Int. Cosmic Ray Conf. (Salt Lake City) vol. 2, p. 96 (1999).
33. Paolo Lipari in Proc. 8th Int. Workshop on Neutrino Telescopes (ed. Milla Baldo Ceolin, 1999) p. 245.